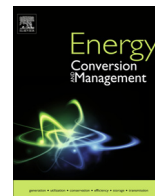




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# Hybrid photovoltaic-thermal solar systems for combined heating, cooling and power provision in the urban environment

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## ABSTRACT

Solar energy can play a leading role in reducing the current reliance on fossil fuels and in increasing renewable energy integration in the built environment, and its affordable deployment is widely recognised as an important global engineering grand challenge. Of particular interest are solar energy systems based on hybrid photovoltaic-thermal (PV-T) collectors, which can reach overall efficiencies of 70% or higher, with electrical efficiencies up to 15–20% and thermal efficiencies in excess of 50%, depending on the conditions. In most applications, the electrical output of a hybrid PV-T system is the priority, hence the contacting fluid is used to cool the PV cells and to maximise their electrical performance, which imposes a limit on the fluid's downstream use. When optimising the overall output of PV-T systems for combined heating and/or cooling provision, this solution can cover more than 60% of the heating and about 50% of the cooling demands of households in the urban environment. To achieve this, PV-T systems can be coupled to heat pumps, or absorption refrigeration systems as viable alternatives to vapour-compression systems. This work considers the techno-economic challenges of such systems, when aiming at a low cost per kW h of combined energy generation (co- or tri-generation) in the housing sector. First, the technical viability and affordability of the proposed systems are studied in ten European locations, with local weather profiles, using annually and monthly averaged solar-irradiance and energy-demand data relating to homes with a total floor area of 100 m<sup>2</sup> (4–5 persons) and a rooftop area of 50 m<sup>2</sup>. Based on annual simulations, Seville, Rome, Madrid and Bucharest emerge as the most promising locations from those examined, and the most efficient system configuration involves coupling PV-T panels to water-to-water heat pumps that use the PV-T thermal output to maximise the system's COP. Hourly resolved transient models are then defined in TRNSYS, including thermal energy storage, in order to provide detailed estimates of system performance, since it is found that the temporal resolution (e.g. hourly, daily, yearly) of the simulations strongly affects their predicted performance. The TRNSYS results indicate that PV-T systems have the potential to cover 60% of the combined (space and hot water) heating and almost 100% of the cooling demands of homes (annually integrated) at all four aforementioned locations. Finally, when accounting for all useful energy outputs from the PV-T systems, the overall levelised cost of energy of these systems is found to be in the range of 0.06–0.12 €/kW h, which is 30–40% lower than that of equivalent PV-only systems.

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## 1. Introduction

The energy problem is multifaceted and complex, and involves a number of important aspects such as the continued increase in the global energy demand in the face of stagnating oil production, price volatility, concerns relating to energy independence, security and economic growth, and a growing awareness of the detrimental effects on health and the environment of releasing combustion products into the atmosphere [1,2]. Renewable energy sources provide

a secure and reliable solution for the decarbonisation of the energy infrastructure, and are associated with significantly reduced cradle-to-grave emissions. However, renewable energy sources currently supply only 14% of the world's total energy [3], with solid biofuels having the largest share, mainly in the non-commercial sector in developing countries.

Solar energy is a clean, abundant and sustainable form of primary energy [4] that can address the energy problem simultaneously from economic, environmental, health and security perspectives [5,6], and the realisation of affordable solar energy systems has been widely acknowledged as a global engineering grand challenge. Within a European framework, where this study

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### Nomenclature

AC	air conditioning	$T_h$	temperature of the fluid entering the storage tank from the heat source [°C]
AR	absorption refrigeration	$T_L$	temperature of the fluid replacing that extracted to supply the load [°C]
COP	coefficient of performance	$T_m$	average temperature of the fluid through the solar collector [°C]
DHW	domestic hot water	$T_{in}$	inlet temperature of the fluid to the solar collector [°C]
HP	heat pump	$T_i$	temperature of the $i^{th}$ storage tank segment [°C]
LCOE	levelised cost of energy	$T_o$	outlet temperature of the fluid from the solar collector [°C]
MPP	maximum power point	$T_{PV}$	PV temperature [°C]
PV	photovoltaic	$T_{PV0}$	PV reference temperature [°C]
PV-T	photovoltaic-thermal	$t$	time [s]
<i>List of symbols</i>		$U_L$	overall thermal loss coefficient of the solar collector per unit area [W/m <sup>2</sup> K]
$A$	total solar collector array aperture or gross area [m <sup>2</sup> ]	$U'_L$	thermal loss coefficient dependency on temperature [W/m <sup>2</sup> K <sup>2</sup> ]
$c_p$	specific heat capacity of the collector fluid [J/kg K]	$\alpha$	short-wave absorptance of the absorber plate [–]
$F_R$	overall solar collector heat removal factor when the efficiency is given in terms of $T_{in}$ [–]	$\alpha_i$	control function defined by $\alpha_i = 1$ if $i = S_h$ , and $\alpha_i = 0$ otherwise [–]
$F_m$	modified value of $F_R$ when the solar collector efficiency is given in terms of $T_m$ [–]	$\beta$	PV temperature coefficient [1/°C]
$I$	global radiation incident on the solar collector (tilted surface) [W/m <sup>2</sup> ]	$\beta_i$	control function defined by $\beta_i = 1$ if $i = S_L$ , and $\beta_i = 0$ otherwise [–]
$M_i$	mass of the fluid in the $i^{th}$ storage tank segment [kg]	$\gamma_i$	control function defined by $\gamma_i = f(\alpha_i, \beta_i)$ [–]
$m$	mass flow rate at use conditions [kg/s]	$\tau$	short-wave transmittance of the collector cover(s) [–]
$m_{test}$	mass flow rate at test conditions [kg/s]	$(\tau\alpha)$	product of the cover transmittance and the absorber absorptance [–]
$m_L$	fluid mass flow rate from the storage tank to the load [kg/s]	$(\tau\alpha)_n$	product $(\tau\alpha)$ at normal incidence [–]
$m_h$	fluid mass flow rate to the storage tank from the heat source [kg/s]	$\eta_{PV}$	PV efficiency [–]
$P_{elec}$	PV electrical power output [W]	$\eta_{TH}$	thermal efficiency [–]
$Q_i$	rate of thermal energy input by the heating element to the $i^{th}$ storage tank segment [W]	$\Delta U_i$	incremental loss coefficient between the $i^{th}$ storage tank segment and the environment per unit area [W/m <sup>2</sup> K]
$T_a$	ambient temperature [°C]		
$S_h$	number of the storage tank segment into which the fluid enters from the heat source, $S_h = 1, \dots, 4$ [–]		
$S_L$	number of the storage tank segment into which the fluid enters when replacing that extracted to supply the load, $S_L = 1, \dots, 4$ [–]		

is focussed, it has the potential to play a leading role in meeting the requirements of European Directives (2010/31/EU, 2012/27/EU) which aim to reduce fossil-fuel consumption and to increase the integration of renewables in the built environment. It can be utilised in a wide range of diverse applications, from providing space heating, hot water and cooking, to generating power for lighting, cooling, and generally for supporting the electrical infrastructure. These attributes have been promoting an increasing interest in academia, industry and governments worldwide in research, innovation and investments related to solar energy technologies [7,8].

Despite its advantages, solar energy remains a small fraction of the world's total energy supply (below 2%) [9]. Most of the global solar-driven generation is in China and OECD countries, with an annual global growth of 46% for PV and 11% for solar thermal, and especially strong growth in Europe [10], as a result of the implementation of policies and subsidies supporting the adoption of relevant technologies. If solar energy is to play a significant role within the energy-mix, this will involve an ever-increasing quantity of distributed energy generation in the urban and built environment. This transition has the benefit of moving generation closer to the point of use, into areas where the population is dense and real estate is expensive, thus reducing the load on the energy distribution infrastructure. In order to maintain a low cost of solar energy generation, it is necessary not only for the solar energy generators to be low cost, but also for the high-quality energy being generated per m<sup>2</sup> of roof coverage to be maximised. This need can be met by hybrid photovoltaic-thermal (PV-T) systems, which

generate both electricity and useful thermal energy from the same aperture area, and can easily be integrated with other energy technologies (conversion, storage, etc.) in order to provide multiple energy outputs while making efficient use of an available roof area. Such hybrid PV-T collectors are capable of reaching overall (electrical plus thermal) efficiencies of 70% or higher, with electrical efficiencies up to 15–20% and thermal efficiencies in excess of 50%, depending on the conditions [11]. Solar systems are resilient to oil/gas price fluctuations and political instability since most of their costs are upfront investment costs while running (operating, maintenance) costs are minimal. Solar systems allow for independence or self-consumption, whereby the user generates the energy required onsite with only limited interaction with the local grid, thus significantly reducing their electricity bills. Self-consumption is only possible when renewable systems are interconnected and the electricity and heat generated in excess is stored or used for multiple purposes [12].

Adding to the advantages offered by solar PV and hybrid PV-T systems are reliability and life-time. These systems can be expected to operate with little deterioration for more than 20 years. Reported observations of operational PV systems have shown a loss in power output of 0.5% per year on average [13], while only 2% of modules installed do not meet manufacturer's warranties after 10 years [14]. At present, a small number of manufacturers are producing PV-T systems, despite the relative immaturity of the technology [15]. In most cases, commercial PV-T systems simply integrate existing PV modules and solar thermal

collectors into a single panel. Overall/total (combined) PV-T efficiencies up to 70% have been reported, with electrical and thermal efficiencies in the range 10–14% and 45–65%, respectively [7]. However, there is room for improvement, as evidenced by the growing body of research into PV designs optimised for PV-T applications and novel absorber-exchanger configurations [11,16].

In most of the current applications of PV-T systems, the electrical output is the main priority, hence, the overall objective is to use the contacting fluid to cool the PV cells, thereby maximising the electrical performance of the system; however, this imposes a limit on the fluid's posterior use for heating or cooling purposes. Nevertheless, optimised PV-T systems can in principle provide combined heating and cooling services in the built environment. Specifically, this technology has the potential to cover a significant fraction of the heating and cooling demands in domestic settings, by coupling PV-T systems to low-carbon heat pumps or absorption refrigeration systems, which are viable alternatives to vapour-compression heat pumps or air-conditioning units. The present paper is concerned with quantifying the potential of PV-T systems to supply heating and cooling services, along with any excess electricity, in a range of European climates and environments.

Traditionally, heating and cooling in buildings have been provided separately, using for example gas boilers and vapour-compression air-conditioning units. In recent years, there has been growing interest in thermally-driven cooling technologies, as a reliable and sustainable alternative for the provision of cooling. These systems require a lower electricity input than vapour-compression systems and do not require the use of chlorofluorocarbon (CFC) and hydro-chlorofluorocarbon (HCFC) refrigerants, which have high global warming and ozone depletion potentials. Absorption refrigeration is a viable thermally-driven technology, which can be coupled with low-grade renewable or waste-heat sources. These systems have lower coefficients of performance (COP = 0.5–0.75 for single-stage units [17,18]) than their vapour-compression counterparts, but are noiseless and vibration-free, environmentally benign, and long-lasting. Among the available absorption-refrigeration working fluids, the lithium-bromide/water working pair is commonly used in air-conditioning (AC) applications, over the range from about 20 W to 10 kW. As an alternative, the water/ammonia working pair is used for small-scale residential or large commercial refrigeration or AC applications [19].

Based on the above, there is a great interest in integrating PV-T systems with absorption-refrigeration technologies in buildings. A particularly interesting option concerns the thermal output of PV-T systems, which would be wasted in periods of the year where the heating demand is low, but which can be used for the provision of cooling. PV-T panels based on flat-plate collector designs can provide hot water at temperatures up to 80–90 °C, which can then be utilised as a heat source for the generator of the absorption unit. Recent studies have shown that COPs of up to 0.8 can be achieved by solar-driven single-stage absorption chillers [20]. Experimental results from solar-driven cooling systems installed in Tokyo have demonstrated system COP values up to 0.5 [21]. Adding to this, research performed by Buonomano et al. (2013) [22] for PV-T cooling in Italy, has shown a 74% reduction in primary-energy use by this system.

An alternative configuration involves the coupling of PV-T systems to small-scale traditional vapour-compression AC units. In this case, the electrical power output of the PV is used to drive the AC system compressor, and the thermal output is used to cover the hot water and space heating demands. As an added benefit, these systems employ conventional, mature and relatively low-cost AC technologies for the provision of heating and cooling, thus increasing their profitability [23].

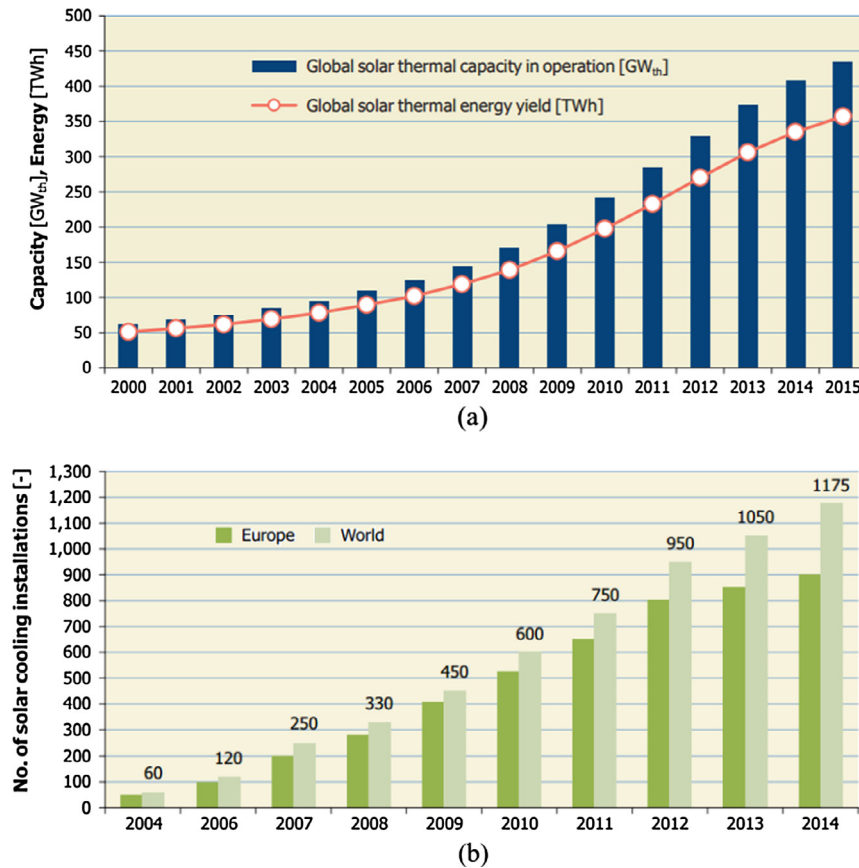
The primary barrier for the market adoption of solar PV-T systems combined with cooling are their high initial costs [24]. However, there is a significant potential for reducing the cost of PV-T modules, which is a major contributor towards the high system capital costs [25,26].

In this context, the present work considers the potential and challenges of hybrid PV-T systems for combined heating/cooling provision to households in the urban environment, which represents the 40% of the energy consumption in the EU. The paper is structured as follows; first a global market analysis of solar-driven co-generation systems is presented, which is followed by an analysis of the technical potential and viability, as well as the affordability of the integration of hybrid PV-T systems in buildings for heating and cooling in ten different locations in Europe. Following preliminary estimations based on these locations, detailed transient hourly simulations for the most promising locations in 3 different climates are conducted in TRNSYS, based on which the levelised cost of energy for the examined cases is then calculated. Finally, the results are discussed and conclusions are drawn.

## 2. Market analysis: Solar-driven heating and cooling

The total worldwide power generation from PV panels has reached a record level of 227 GWe. Key players in the adoption of PV technology have been Japan, China and the USA, while a few countries in Europe have an installed capacity capable of covering up to 8% of their national total demands. In particular, the power generation from PV in Italy corresponds to 7.8% of the total demand, in Greece it amounts to 6.5% and in Germany to 6.4% of the total demand. At the same time, the thermal energy generated to-date by solar-thermal collectors amounts to 435 GWth, which corresponds to savings of 116.4 million tons of CO<sub>2</sub> [27] (see Fig. 1a). In 2015, the amount of hot water generated by solar collectors increased by more than 6%, even though there was a market slow-down in China, where 77% of all new installations are located, and also in Europe, where Cyprus, Greece, and Austria are market leaders [28]. Looking at the 2014 market trends, the solar thermal industry has shrunk, in particular in Germany, due to a slow-down in the construction sector, a reduction in gas prices, and insufficient incentives and schemes, which have led to increased difficulties for the financing of solar (but also other renewable) projects.

Compared to the PV market, the installation of solar-thermal systems in the EU has not experienced the same growth. For example, approximately 230 million m<sup>2</sup> of PV had been installed for 16.5 million m<sup>2</sup> of solar-thermal collectors in Germany by 2012 [29]. This trend is attributed to the lack of incentives, financial support, education and knowledge [27]. Therefore, in the majority of EU countries there is an opportunity for large solar-thermal market development. In Cyprus, which has the highest global solar-thermal penetration per capita, the generated thermal energy from solar collectors corresponds to 480 Wth per capita, whereas in other countries with high solar potential, such as Italy and France, this number is less than 10 Wth [30]. The experience gained from solar-thermal installations in countries such as Cyprus, Greece and Austria, indicates the great potential of such systems for utilising solar energy, and that this potential is still far from having been exploited. This utilisation should increase by 45% in order to meet the 2020 targets set in the EU [28]. Furthermore, although the focus as far has been on electricity generation, the provision of heating and cooling from renewable sources of energy is a necessary requirement of meeting the ambitious decarbonisation target. In this context, some of the most promising applications for thermal systems are in the domestic and industrial sectors, which can have either distributed heating and cooling generation, or be connected to district heating and cooling networks.



**Fig. 1.** (a) Worldwide solar thermal installed capacity and energy yield, for the years 2000–2015 [27]. (b) Solar cooling air-conditioning systems market growth worldwide for the years 2004–2014 [31].

Heating and cooling correspond to approximately 50% of the total final energy use in the EU. Solar-thermal systems can provide hot water at temperatures up to 150 °C, and have the potential to cover a large fraction of the demand for heating, hot water and possibly cooling. In winter, the heating demand is high but the solar resource is less abundant, while in summer the diurnal profile of the solar irradiance follows closely that of the cooling demand, which is currently covered by vapour-compression systems in most cases [30]. The use of conventional refrigeration systems (electric heat-pumps, chillers, etc.) can give rise to a high electrical consumption, which could be covered by PV or PV-T systems. Therefore, there is great potential in primary energy savings and energy bills reduction by integrating PV, or PV-T systems into buildings for the provision of power, heating and cooling.

The market for solar-driven cooling via thermal technologies (absorption/adsorption refrigeration) is at an early stage of maturity, with approximately 1175 systems installed worldwide (as of the end of 2014), as shown in Fig. 1b [31]. The market experienced significant growth between 2004 and 2014, but the annual growth rates have decreased from 32% in 2007–2008 to 12% in 2013–2014. More than 75% of the installations worldwide are located in Europe, led by Spain, Italy and Germany. The vast majority of the installed solar air-conditioning systems are coupled with either flat-plate collectors or evacuated-tube collectors. Limited examples of the use of concentrated collectors (Fresnel or parabolic-trough types) can be found in installations in India, Turkey and Australia [31]. To-date there is still a small number of companies that offer packaged solar air-conditioning systems. The majority of the systems currently available include independent components that have been installed together on-site to meet the specific

needs of different projects. In order for solar air-conditioning solutions to become broadly available, there is need for growing expertise in installing, commissioning and operation of such systems [32].

### 3. Modelling framework and methodology

The work presented in this paper is aligned with the Solar Heating and Cooling roadmap of the International Energy Agency (IEA), as the proposed solutions will cover at least 60% of the combined space heating and domestic hot water (DHW) demand [33] as well as about 50% of the cooling demand. To achieve this, PV-T systems are considered which are coupled with small-scale thermally-driven solar-cooling systems (absorption refrigerator or heat pump) and thermal energy storage to increase the system's autonomy. Fig. 2 shows the general layout of the solutions proposed in this work.

In the calculations below, a household size of floor area 100 m<sup>2</sup> is considered (4–5 people) [34], and it is assumed that the percentage of roof area available for each single-residence dwelling is about 50% of the household's total floor-area [34], which in the present case study is equivalent to an available area of 50 m<sup>2</sup>. The electrical and thermal efficiencies of the PV-T system are independent of location, however, the irradiation and also, to a lesser extent, ambient conditions (temperature, wind speed) will strongly influence the total generation. The electrical and thermal efficiencies are considered to vary in the ranges 18.0–15.3% and 60–50%, respectively, for operating temperatures between 25 and 85 °C. In order to maintain high electrical efficiencies at higher temperature-levels, PV cells suitable for operation at elevated



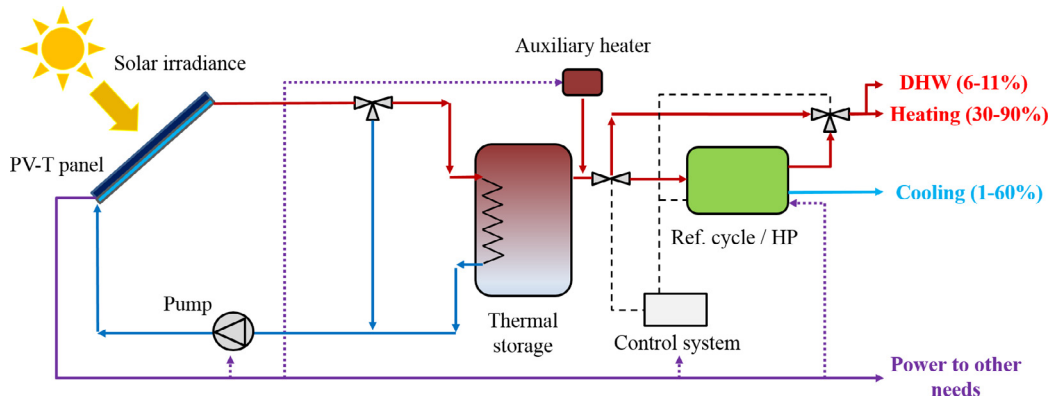


Fig. 2. Schematic diagram of the proposed PV-T system for solar heating and cooling provision.

temperatures are required. In this study, the use of hetero-junction thin-film (HJT) PV cells is proposed, as they retain high efficiencies at elevated temperatures, with the added benefit of holding the record for Si-based PV cell efficiency (25.6%) [35,11].

The paper is organised as follows:

- Firstly, ten European locations are selected, and the potential electrical and thermal outputs of PV-T systems based on the local annual and monthly irradiance data are estimated (Section 4).
- Four different system configurations coupling PV-T to a number of alternative air-conditioning (AC) technologies, are then evaluated (Section 4).
- The most promising locations and PV-T system configuration are selected to perform detailed transient simulations in TRNSYS (Section 5).
- The economic viability of the solutions is then assessed based on their levelised cost of energy (LCOE) (Section 6).
- Finally, a summary of the important results along with their interpretation and interesting implications are provided (Section 7).

#### 4. Potential of PV-T systems for combined heating and cooling in domestic applications

PV-T systems can be optimised to provide the maximum coverage of the heating (including space heating and DHW) and/or cooling demands in buildings in a variety of different configurations. PV-T systems may be coupled to thermally-driven absorption refrigeration (AR) systems as viable alternatives to vapour-compression refrigeration systems, or to electrically-driven heat pumps (HP), where the PV-T collectors are used to provide both the electrical input to the HP and/or the thermal input to these systems at a heat-source temperature that maximises the system's performance indicators.

##### 4.1. Assessment of the overall output of PV-T systems in domestic applications

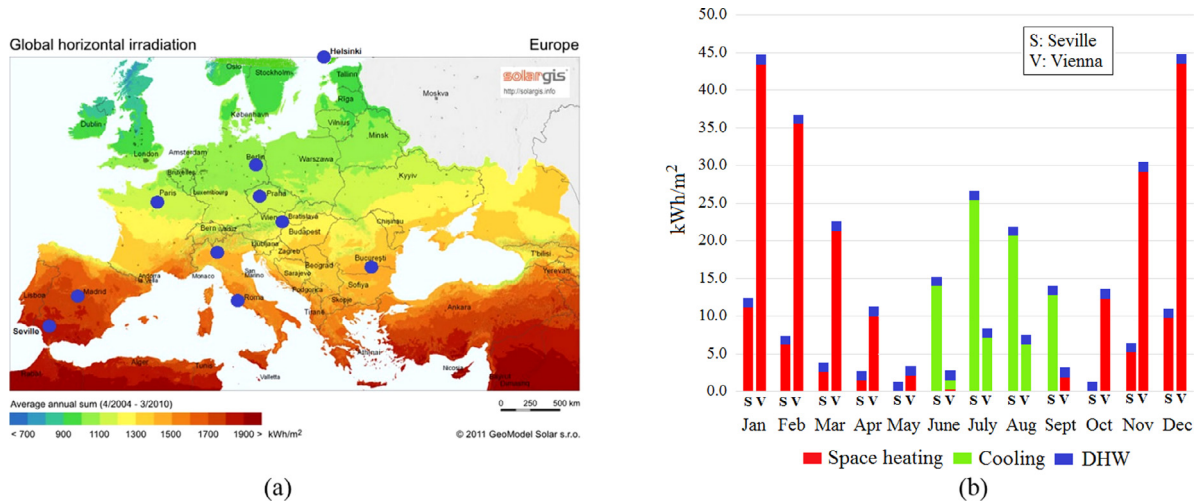
Based on the above, calculations using the demand [36] and irradiance data [37] for ten different locations in Europe have been performed in order to evaluate the potential of PV-T + HP/AR combined systems for covering the space heating/cooling and DHW energy demands in urban environments. The locations have been chosen to cover different climatic regions, as well as different demand profiles. Fig. 3a overlays the selected locations in Europe (Seville, Madrid, Rome, Milan, Bucharest, Vienna, Paris, Prague, Berlin and Helsinki) with a global horizontal irradiation map. The

space heating/cooling and DHW demand profiles of two of the selected locations as well as the annual global irradiation profiles are presented in Fig. 3b. It can be seen that the requirement for cooling decreases with latitude, with the cooling demand being greater than or equal to the space heating demand in southern regions and close to zero in the most northerly regions. The DHW demand, on the other hand, shows little variation between the locations, and is approximately constant throughout the year.

Table 1 shows estimates of the potential of the proposed PV-T system (as described above, e.g. in Fig. 2) to cover: (i) the combined space heating and DHW demand; and (ii) the cooling demand, for a particular case study (Scenario 1) in which the PV-T system is sized such that the thermal output of the system can cover 60% of the space heating and DHW needs, while the electricity generated is used to drive a conventional split unit (air-to-air vapour-compression refrigeration cycle) that covers the cooling demand. This scenario, which is described in further detail below, has been chosen as the representative one since it is amongst the most commonly proposed scenarios in the literature [11,15]. The calculations have been performed over an annual period, based on annually averaged irradiance and energy-demand values. The aim of these initial calculations is twofold; firstly, to explain the procedure used to obtain the results of the detailed calculations that follow, and secondly, to highlight the importance of considering higher resolution monthly/daily data when evaluating the feasibility of these systems, as will be discussed below. It is noted that deviations between the annually- and monthly-averaged calculations for Scenarios 2–4 would be similar to those presented below for Scenario 1.

A number of interesting conclusions can be drawn from Table 1. There are important differences in the annual global solar irradiance within Europe, and these are not only dependent on the latitude of a particular location, but also on other climatic, atmospheric and geographical conditions; e.g. the irradiance in Prague (latitude 50.1 N) is lower than in Helsinki (latitude 60.2 N), while in Vienna (latitude 48.2 N) and Rome (latitude 41.9 N) they are virtually identical. Relative to its total energy demand (for space heating/cooling and DHW), Seville has the highest cooling demand, which represents 59% of the total, followed by Rome and Madrid with 35.7% and 28.6%, respectively. Milan and Bucharest have more moderate cooling demands of 15.5% and 13.2% of the total, while Berlin, Prague and Helsinki have cooling demands corresponding to less than 5% of the total. The DHW demand is similar in all locations and accounts for about 6–12% of the total.

The annual electrical and thermal outputs per unit area in Table 1 are directly related to the annual global irradiation in each location. The calculated PV-T array area requirement to cover 60%



**Fig. 3.** (a) Selected locations and global horizontal irradiation in Europe [38]. (b) Space heating, DHW and cooling demands and global irradiance profiles for Seville and Vienna [36,37].

**Table 1**

Solar irradiance, PV-T area necessary to cover 60% of the space heating and DHW demands, electrical and thermal energy generation and percentages of the heating and cooling demands covered for ten different locations in Europe. Notice that the numbers presented in this table correspond to annually integrated data.

Location	Irradiance [kW h/m <sup>2</sup> ]	PV-T area [m <sup>2</sup> ]	Electricity generation [kW h/m <sup>2</sup> ]	Thermal energy generation [kW h/m <sup>2</sup> ]	Space heating and DHW covered [%]	Cooling covered [%]
Seville	2101	2.7	350	1156	60	38
Madrid	1866	7.0	311	1026	60	>100
Rome	1119	8.1	186	615	60	98
Milan	998	19.5	166	549	60	>100
Bucharest	1457	15.4	243	802	60	>100
Vienna	1110	21.4	185	610	60	>100
Paris	995	21.2	166	547	60	>100
Prague	839	33.4	140	461	60	>100
Berlin	960	21.1	160	528	60	>100
Helsinki	843	23.7	140	464	60	>100

of the combined space heating and DHW demand for Scenario 1 is also shown. In all of the studied locations, a 50 m<sup>2</sup> area is more than sufficient to cover 60% of the space heating and DHW needs, with less than 10 m<sup>2</sup> of PV-T array required in the southern-most locations and between 15 and 24 m<sup>2</sup> required in the more northerly locations (with the exception of Prague for which 33 m<sup>2</sup> is required). Furthermore, it is also found for Scenario 1 that the total electricity generated is greater than that required to cover cooling demand in most of the locations, with the exception of Seville (38% covered) and Rome (98% covered), where relatively small areas are used.

The calculations above demonstrate that PV-T systems have the potential to cover a significant fraction of the space heating/cooling and DHW needs in urban settings. However, these calculations need to be refined before they can provide more accurate evaluations of the feasibility of these systems, since they have so far assumed that all of the energy generated can be used. To do so, thermal and electrical storage needs to be considered. Electrical storage in domestic systems can be avoided if the household is connected to the grid, so that when electricity generation exceeds demand, surplus electricity can be exported. Moreover, the covering factor of the PV-T system (defined as the fraction of area of the thermal collector covered with PV cells) can be adjusted to cover the electricity demand while minimising any excess. Surplus electricity may also be used to cover a fraction of the remaining household electrical demand (e.g. for lighting, cooking, electrical devices, etc.), or for additional heating provision (e.g. by means of an electrically-driven HP). Meanwhile, the thermal-energy subsystem

allows low-cost, low-complexity and environmentally friendly thermal energy storage (e.g. a hot water tank) to be implemented, leading to flexible systems that can balance the overall energy output and demand.

An alternative means of balancing the mismatch between generation and demand, and of minimising the installed capacity on-site, is seasonal storage. However, these systems are often infeasible in the urban environment, mainly due to space constraints. Therefore, domestic energy systems are typically sized considering daily (or a few days at most) storage capacity. Since the generation and demand profiles will vary depending on the climate conditions and domestic needs, respectively, the sizing of the system varies with location. The system could be sized for covering at least a certain percentage of the energy demand annually, minimising the excess of energy throughout the year or minimising the cost for the final consumer. Typically, all the former conditions are balanced for the sizing of a domestic system. External elements such as subsidies, taxes, environmental policy will also influence this decision (see Section 6).

#### 4.2. Assessment of the complete PV-T system coupled with heating and cooling technologies

For each of the ten selected European locations examined above, a PV-T system capable of covering at least 60% of the combined annual heating (space heating and DHW) demand is sized using higher resolution monthly-averaged demand/generation data. It is also assumed that a thermal store sized for the daily

demand is installed, and that the household is connected to the grid, such that there is no need for electricity storage. The percentage of the covered heating and cooling demands and the excess of both electricity and thermal energy are calculated for four different scenarios, based on which the system configuration (e.g. with PV-T collectors coupled to an electrically-driven or thermally-driven refrigeration cycle) most suitable for each location is evaluated. The four different scenarios considered in the present work are described below.

#### 4.2.1. Scenario 1. PV-T and electrical air-to-air heat pump (HP) unit covering the cooling demand only

In this scenario, the thermal output of the PV-T system is used to cover the space heating and DHW demands (prioritising DHW, which is almost constant throughout the year), and the electricity generated is used to cover the cooling demand by means of a small-scale (<10 kW) air-to-air HP unit (split heat-pump unit). The thermal storage tank and the piping are assumed to be perfectly thermally insulated with no losses.

To evaluate the proportion of the household demand covered by the system, the energy performance of the air-to-air AC unit is also required. The AC efficiency in cooling mode ( $COP_c$ ) is calculated as the ratio of the cooling load the heat pump provides over the total power input to the heat pump unit. The  $COP_c$  of the air-to-air HP unit for cooling provision is considered constant throughout the year and equal to 3 [39]. This figure is an average value used across all the localities investigated, while in real applications the  $COP_c$  will vary from 2 to 5 depending on the ambient air temperature and part-load conditions. Further, it is assumed that no electricity is consumed in delivering DHW and space heating, although in real applications electricity will be consumed by circulation pumps and possibly a resistive heating element (located inside the thermal storage tank) for supplementary heating when the water temperature is below 60 °C for DHW and 50 °C for space heating. It should be noted that solar-thermal systems are compatible with existing domestic water tanks (thermal storage) or gas boilers; both systems are typically found in European households.

#### 4.2.2. Scenario 2. PV-T and electrical air-source HP covering both the heating and cooling demand

In this scenario, the thermal output of the PV-T system is used to cover the DHW demand, while cooling and space heating demands are covered by means of a refrigeration cycle. The same air-to-air unit can operate in heating or cooling modes. The HP unit efficiency in heating mode is calculated using the Coefficient of Performance (COP). The COP is the ratio of the heating load the AC provides over the total power input to the unit. The HP efficiency values used in this scenario are 3.5 for the COP and 3 for the  $COP_c$  [39]. Similar to Scenario 1, these COP values are average values, to reflect the broad range of climatic conditions of the locations investigated in this study. These split-unit systems are commercially available at small scales (below 10 kW), suitable for domestic applications.

#### 4.2.3. Scenario 3. PV-T and electrical water-to-water refrigerating cycle/AC

Here, the DHW needs are covered by the PV-T thermal output, while the heating and cooling needs are covered by an electrically-driven water-to-water HP unit. The HP unit uses as heat source the thermal output from the bottom of a water-storage tank (kept at a constant temperature of 15 °C by the PV-T system). Since the inlet water temperature to the evaporator of the HP unit is maintained at a constant temperature of 15 °C over the entire winter period, the COP in the heating mode is considered constant and equal to 5. Similarly, in cooling mode the condenser of the HP unit releases heat to a constant thermal environment

at 15 °C, which allows the HP unit to provide cooling with an  $COP_c$  of up to 6 [40], reducing significantly the power input requirements. The former assumption has been proven to be correct as results in Section 5 will demonstrate.

#### 4.2.4. Scenario 4. PV-T and AR

In this scenario, the thermal output of the PV-T system is used to cover DHW, cooling and space heating demands, again while prioritising the DHW demand (in all the cases when there exists cooling demand there is no space heating demand, and vice versa). In this case a thermally driven AR unit covers the cooling demand, which is assumed to have a COP of 0.7 and to require an inlet temperature of 80–90 °C [41]. For the thermally driven cooling technologies, the COP is defined as the ratio of the provided cooling over the thermal input to the system generator. These systems are available at small scales, between 7.5 and 15 kW. Here we consider that no electricity is necessary to cover the thermal and cooling demands, however, in a real application a small amount of the generated electricity will be consumed by a resistive heater (thermal storage tank) and by the cooling unit circulating pump. In all the examined scenarios the problem formulation includes 5 key variables: the area of the PV-T panels, the percentages of the annually-averaged DHW and space-heating demands covered, the cooling demands covered, and the excess thermal and electrical outputs generated. The maximum available area is 50 m<sup>2</sup> and in all cases the objective is to cover at least 60% of the combined DHW and space heating demand. The excess electricity will not be constrained, for the reasons explained above, while it is desirable for the excess thermal energy not to exceed 65% of the overall generation. It should be noted that since these variables are dependent, in some cases it is not possible to fulfil all constraints; in such cases, the limiting constraint is the available area.

The results obtained for the four scenarios described above are presented in Table 2. The results summarised in this table correspond to annually integrated monthly-averaged values, and do not consider seasonal thermal storage (since in a practical domestic system this is not considered here as being feasible); thus, any thermal and/or electrical energy excess will occur when the energy generation is greater than the thermal and/or electrical demand (which typically occurs during summer). It can be observed that for Scenarios 1, 2 and 4, only in the first three cases, namely Seville, Madrid and Rome, it is possible to cover more than 60% of the DHW and space heating needs, and in Scenario 3 this is also possible in Bucharest; however the PV-T area needed is more than double that for Rome and Madrid and more than 4 times that for Seville. In these four locations, the percentage of cooling demand covered is similar for all scenarios: approximately 100% in Madrid, Rome and Bucharest; and between 21.2 and 40.4% in Seville, where the percentage of cooling demand annually is greater than the space heating and DHW demands (see Table 1). For the rest of the locations, the data in Table 2 indicate that significant areas are needed to cover an important part of the DHW and space heating demands, also leading to high thermal energy excess. Therefore, the systems proposed in Scenarios 1, 2 and 4 will not be considered feasible in those locations, despite the initial calculations for Scenario 1 presented in Table 1. The deviations between the results in Tables 1 and 2 (Scenario 1) highlight the importance of considering the monthly variabilities in both the demand and generation profiles. Not considering the former leads to an overestimation of the performance of the solar-based systems. An excess of thermal and electrical energy occurs mainly because the amount of energy generated over the summer (due to higher irradiance) is more than enough to cover the cooling and DHW needs. Since seasonal storage is not considered, this excess cannot be used in the winter when higher heating demands are reached. In the case of Seville, the PV-T area required to cover 60% of the space heating and

**Table 2**  
Feasibility of Scenarios 1–4, for covering the space heating, DHW and cooling demands in different locations in the EU. Results summarised in this table correspond to monthly calculations integrated annually.

Location	Scenario	Seville	Madrid	Rome	Milan	Bucharest	Vienna	Paris	Prague	Berlin	Helsinki
PV-T area [m <sup>2</sup> ]	1	6.5	21.9	31.5	50.0	50.0	50.0	50.0	50.0	50.0	50.0
	2	6.5	21.9	31.5	50.0	50.0	50.0	50.0	50.0	50.0	50.0
	3	4.3	15.9	20.7	50.0	40.7	50.0	50.0	50.0	50.0	50.0
	4	5.4	20.6	28.2	50.0	50.0	50.0	50.0	50.0	50.0	50.0
DHW and space heating covered	1	60.0%	60.1%	60.2%	35.7%	53.6%	42.8%	45.7%	33.8%	32.4%	32.4%
	2	60.0%	60.1%	60.2%	35.7%	53.6%	42.8%	45.7%	33.8%	32.4%	32.4%
	3	60.1%	60.0%	60.1%	42.1%	60.0%	50.9%	58.6%	44.5%	42.3%	42.3%
	4	60.0%	60.1%	60.1%	38.1%	55.1%	44.7%	47.9%	35.9%	35.0%	35.0%
Cooling covered	1	44.4%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	2	44.4%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	3	54.5%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	4	21.2%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Overall electricity excess	1	56.9%	74.9%	74.0%	87.0%	91.5%	94.8%	97.0%	97.6%	99.5%	99.5%
	2	29.2%	49.8%	54.1%	68.5%	67.3%	68.9%	69.0%	64.2%	78.0%	78.0%
	3	15.0%	35.5%	36.4%	50.4%	46.6%	49.1%	47.6%	44.2%	49.4%	51.9%
	4	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Overall thermal energy excess	1	59.3%	68.2%	74.5%	77.1%	72.7%	69.8%	68.0%	62.6%	74.5%	74.5%
	2	81.0%	93.3%	92.3%	94.4%	96.1%	94.9%	94.3%	93.3%	93.0%	93.0%
	3	–	–	–	–	–	–	–	–	–	–
	4	20.1%	24.2%	26.7%	23.5%	32.6%	41.2%	37.7%	20.4%	28.0%	28.0%

DHW demands is small and could be reasonably increased. Increasing the PV-T area to 12 m<sup>2</sup> allows 83.7–98.9% of space heating and DHW and 52.5–100% of cooling demand to be covered, with best performance obtained by Scenario 3. Scenario 3 also results in the smallest area requirement to cover a given percentage of energy needs and, consequently, is the scenario that leads to the lowest overall electricity and thermal energy surplus. It should be noted that in this case it is assumed that almost all of the thermal output from the PV-T is used to maintain the COP of the water-to-water HP unit high, as explained above.

## 5. High-resolution transient modelling of PV-T combined heating, cooling and power systems

Scenario 3 emerges as the most promising PV-T system configuration from the results in Section 4 (Table 2). Therefore, this scenario was selected for further study in three different locations (Seville, Rome and Bucharest). Detailed, transient calculations of the PV-T system's operation and performance were conducted on a daily basis, and the sizes of the main components of the complete system (other than the PV-T array) were calculated. Higher resolution hourly weather data were considered in this part of the study, and hourly demand profiles were generated, in agreement with the monthly data available from Ref. [36]. Typical demand and daily profiles were obtained from Refs. [42,43], which were used to calculate the hourly demand profiles over a typical day for each month of the year. Transient simulations for the selected locations, over a full year, were conducted in TRNSYS [44]. For each location, the PV-T array size was set equal to the minimum necessary to cover the target 60% of the combined space heating and DHW demand reported in Table 2. The resulting hourly/daily calculation results are compared in this section to the results in Table 2, and used to assess whether the assumptions made earlier are realistic and justified.

### 5.1. Model

Fig. 4 shows the model defined in the TRNSYS [44] environment, also indicating the element types used. The diagram in Fig. 4 has been simplified for clarity. The main elements are the

PV-T panel, the HP and the water tank (thermal store). In addition, a pump and a controller unit are included in the model.

The solar collector unit corresponds to a standard flat-plate PV-T collector. The thermal efficiency of the collector is defined in Eq. (1), which considers a linear dependence of the loss coefficient  $U_L$  with  $(T_{in} - T_a)$  as per Eq. (2). The overall collector heat removal efficiency factor  $F_R$  is defined in Eq. (3), and depends on the average fluid temperature through the collector, the flow rate in test conditions, the specific heat capacity of the collector fluid, the transmittance of the collectors cover(s) and the absorptance of the absorber plate. Thus, this model considers the angular dependence of the transmittance and the effect on the thermal losses of the ambient temperature, wind speed and irradiance conditions (hourly defined by type 15–6).

$$\eta_{TH} = F_R(\tau\alpha) - F_R U'_L \left( \frac{T_{in} - T_a}{I} \right) \quad (1)$$

$$U'_L = U + U_L(T_{in} - T_a) \quad (2)$$

$$F_R(\tau\alpha) = F_m(\tau\alpha) - \left( \frac{m c_p}{m_{test} c_p + \frac{F_m U'_L}{2}} \right) \quad (3)$$

The operating point of the PV array is assumed to be kept near the maximum power point (MPP), and its electrical performance is obtained from Eqs. (4) and (5), where the efficiency at reference conditions and the thermal coefficient are 0.18 and 0.3 K<sup>−1</sup>, which correspond to Silicon-based HJT PV technology [33,11].

$$\eta_{PV} = \frac{P_{elec}}{IA} \quad (4)$$

$$\eta_{PV} = \eta_o [1 - \beta(T_{PV} - T_{PVo})] \quad (5)$$

The water tank is modelled as consisting of  $N$  fully-mixed equal-volume segments. In the present case,  $N$  was set to 4. In addition, the tank includes an auxiliary heater with which to reach the minimum DHW temperature requirements (water should be heated up to minimum 60 °C for DHW uses). The fluid streams flowing up and down from each node are assumed to be fully mixed before they enter each segment, thus, the energy balance written for the  $i^{th}$  tank segment can be expressed as shown in Eqs. (6) and (7), where the energy supplied to the tank from the





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In Rome, a 20.7-m<sup>2</sup> PV-T system is considered, the size of the water tank is 0.15 m<sup>3</sup> and a 6.2-kW HP unit. The maximum outlet temperature from the PV-T system is 78 °C (sunny day in summer). In this location, the minimum temperature of the bottom of the water tank is slightly above 16 °C; thus again the HP unit performance assumed in Table 2 for this scenario is feasible.

In Bucharest, a 40.7-m<sup>2</sup> PV-T system is considered, the size of the water tank is the same as above and a 5.0-kW HP unit. The maximum outlet temperature from the PV-T system is about 80 °C (sunny day in summer). The temperature of the bottom of the water tank is again all year slightly above 15 °C; thus even for this location the HP unit performance used in Table 2 is feasible.

Finally, Fig. 5 shows example performance profiles of the PV-T system during a cloudy summer day and a sunny summer day in Rome, with the power output (in kJ/h) (in red) and the outlet fluid temperature of the PV-T system (in blue). It can be observed that the shape of the curves are in agreement with the temperature/power levels discussed above.

## 6. Lowering the cost of energy generation of PV-T systems: Current challenges and barriers

The costs of solar-thermal, PV and PV-T modules and systems were estimated from price lists available from solar retailers in the EU. The main costs of solar-thermal systems are associated with the storage tank, the collectors, the solar fluid, the pump station (consisting of a circulation pump, a controller and temperature sensors) and the piping and fixings. The running costs of these systems is around 120 €/year [45], which represents roughly 10% of their total investment costs. The main fixed costs of PV systems are associated with the PV modules, the inverter, the roof fixing, cables and the meter. The costs of the electrical installation of a PV system were taken from price lists for roof-mounted PV kits reduced by the cost of the PV module. The installation of solar-thermal systems and PV systems amounts to ~1800 €. From the costs listed in Table 4, a solar thermal system consisting of a 150-L tank and a flat-plate solar collector array of 4 m<sup>2</sup>, or with 20 evacuated tubes, would cost ~4800 €, a 3-kW (peak) PV system would cost ~5400 € (both costs include the installation). A 3-kW PV-T system with a 150-L storage tank would cost on average ~10,920 € including the installation. It should be noted that the cost of the PV-T module is 85% higher than the cost of the PV module per kW installed. The cost of the PV-T array accounts for 56% of the total investment costs, the electrical components (inverter, meter, cables, etc.) are 4% of the total installation and the rest of the costs are attributed to the hydraulic components. By comparison, the cost of the PV modules accounts for 87% of a PV

**Table 4**

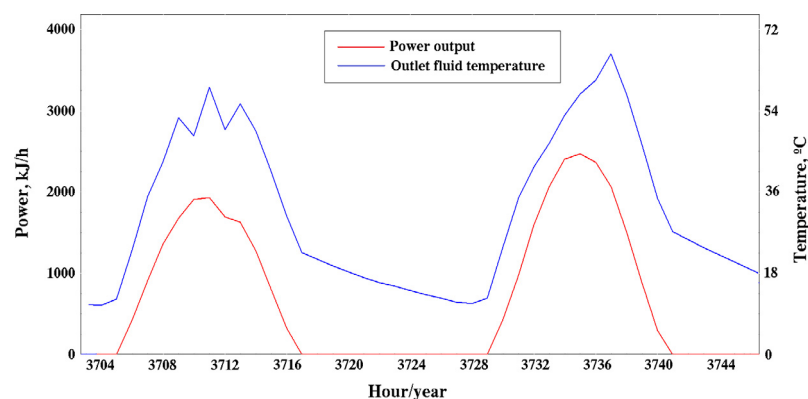
Capital costs incurred for the solar thermal, PV and PV-T systems.

	Range	Average	Reference
<i>Hydraulic components of solar thermal systems</i>			
Pump station	200–650 €	360 €	[50,51]
• Circulation pump	65–270 €	167 €	[50,51]
• Controller	110–258 €	170 €	[50–53]
Expansion vessel	140 €	140 €	[52]
Tank	4–25 €/L	7 €/L	[53–55]
Pipes	11–29 €/m	19 €/m	[50–52]
Fluid	1.2–4.3 €/L	3.3 €/L	[51,52,54]
Mounting	59–244 €/collector	171 €/collector	[51,52]
Installation	1800 €		[46]
<i>Solar collector</i>			
• Evacuated tube	12–52 €/tube	29 €/tube	[50–54]
• Flat plate	158–180 €/m <sup>2</sup>	169 €/m <sup>2</sup>	
<i>Electrical components of PV systems</i>			
• c-Si PV kit	745–1644 €/kW	1183 €/kW	[52,56,57]
• c-Si module	943–1160 €/kW	1036 €/kW	[52,53]
• Electrical components	146 €/kW	146 €/kW	[52]
• Cost of PV-T modules	1680–2520 €/kW	1920 €/kW	[48,58]
• System installation	1800 €	1800 €	[46]

installation, and the thermal collectors account for 14% of the total initial costs of a solar thermal system.

The costs of various types of commercially available heat pumps were reported in Refs. [46,47] and taken from a Daikin pricelist [39]. From the data reported in the study and the manufacturer's price list, the average capital cost for air-to-air heat pumps is 800 €/kW for an installed capacity below 10 kW, and 700 €/kW for an installed capacity of 10–20 kW. Water-to-water heat pumps were only available from 20 kW capacities and upwards at a price of ~6000 € for a 20-kW unit. These units are presently for larger installations rather than a single house, and as a consequence the prices for air to water heat pumps is considered in this study. It is expected that the cost of small scale water to water heat pumps will be similar to a water to air heat pump as the operating principle is the same. The difference will be in the design of the heat transfer coil, which will be an immersed heat exchanger in the water tank in the second case. For air to water heat pumps, costs in the region of 600 €/kW were found for a small units, and a higher cost of 2380 €/kW was found for a 5–10 kW unit. Few models of small scale (<20 kW) thermally driven chillers are available. A list of commercially available units is available in Ref. [16], for which the average cost is 5000 €.

Applying the cost data listed in Table 4 to the various scenarios studied in Section 4, the overall/total levelised cost of energy



**Fig. 5.** Hourly-resolved PV-T panel performance over two days in June in Rome (cloudy day left and sunny day right): power output (red line) and outlet fluid temperature (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(LCOE) over 20 years of operation was calculated in three low-latitude locations: Seville, Madrid and Rome. The LCOE is defined as the net present value of the unit-cost of energy over the lifetime of a generating asset, and can be obtained from Eq. (8), where  $I_t$  is the investment expenditures in year  $t$  (including financing),  $M_t$  includes the operations and maintenance expenditures,  $E_t$  is the combined energy generation,  $r$  is the discount rate and  $n$  is the life of the system.

$$\text{LCOE} = \frac{\sum_{t=1}^n \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (8)$$

All the scenarios defined in Section 4 have a LCOE between 0.06 and 0.12 €/kW h, with the minimum in Seville and the maximum in Rome. The LCOE is mainly influenced by the size of the PV-T system, which is larger in Rome, leading to a higher cost of installation for the electrical part of the system. These values are calculated using annual average data and by assuming a size for the absorption chiller or the heat pump split unit of 3–6 kW. The levelised cost of the energy generated under the assumptions listed in Section 4 is lower than the LCOE generated from small-scale PV in Europe, which depending on the region varies between 0.10 and 0.20 €/kW h [48,49].

As mentioned in the introduction section, the primary barrier for the market adoption of solar PV-T systems combined with cooling is their high initial costs. As discussed above, a 3-kW PV-T system costs twice as much as a PV system of the same installed capacity [24]. At the same time, there is a significant potential for reducing the cost of PV-T modules, which is a major contributor towards the high system capital costs [25,26]. One possibility is to adopt cheaper materials for manufacturing the module (e.g. plastics) and another involves increasing the thermal efficiency of the module with the development of new designs of solar cells as proposed in Ref. [16]. As a consequence, a smaller PV-T module will provide a higher thermal output with a reduction in the levelised cost of the energy. Due to the lack of local retailers and trained installers, the installation costs can account for around 15% of the total installed cost of a PV-T system (data from EU market) [24,46]. High initial costs limit a widespread adoption of the technology also as a consequence of the split incentive (also called the tenant-landlord dilemma). This arises when the person paying for the initial costs is not benefiting from the bill savings. Another limiting factor is represented by the additional components required as backup and storage. These consist of electrical resistance or conventional boilers together with thermal storage. The use of these components might result in high electricity consumption at low efficiency. The main issue associated with having a store is that it requires a large unoccupied area which might not be available in single-family houses.

High initial costs, together with uncertainties caused by poor knowledge of the technology due to its limited application, limits the growth of the market for hybrid PV-T systems for combined cooling and/or heating applications. From the market analysis performed in the present work, it was found that there are technical limitations associated with scaling these systems and the components associated to PV-T applications. For example, commercially available thermally driven chillers do not generally exist for cooling capacities of <20 kW, with existing units limited to only a small number of applications [59]. Finally, local and international policies will definitively overcome the barriers associated to the costs. Projects that demonstrate the operation of such systems should be encouraged, supported and advertised in order to fill these gaps and improve the confidence towards solar PV-T systems.

## 7. Further discussion and conclusions

Solar energy is an abundant and clean renewable energy form with a significant potential to enable a sustainable energy future, and the realisation of affordable solar energy systems is widely acknowledged as an important global engineering grand challenge. The development and broad deployment of affordable solar technologies can, amongst other: (i) enhance sustainability; (ii) reduce pollution; and (iii) increase energy security and independence. Hybrid PV-T systems are particularly promising, especially when overall efficiency is of prime importance and/or the available area is restricted, e.g. in densely populated or urban regions. PV-T collectors are capable of reaching overall (combined electrical plus thermal) efficiencies of 70% or higher, with electrical efficiencies up to 15–20% and thermal efficiencies in excess of 50%. In the urban environment, there is strong evidence that PV-T systems can cover more than 60% of the combined heating demand, including that for space heating and DHW, and more than 50% of the cooling needs of households over reasonable installation areas. This paper has assessed the technical potential and basic economic implications of integrating PV-T systems in the domestic sector, specifically with regard to the provision of combined heating, cooling and power.

The feasibility and affordability of PV-T systems coupled with small-scale thermally or electrically driven solar heating and cooling systems (absorption chillers or heat pumps) has been investigated, also featuring the use of thermal energy storage. The proposed solutions have been studied in 4–5 person households, with a 100 m<sup>2</sup> floor area and 50 m<sup>2</sup> rooftop area available for installation of solar collectors, in ten selected European locations with distinct climatic conditions, using annualised data of varying temporal resolution. Four different system configurations have been analysed, and their performance has been assessed.

Seville, Rome, Madrid and Bucharest proved to be the most promising for the installation of PV-T systems. The most efficient system configuration involves the coupling of PV-T panel arrays to water-to-water heat pumps. The electrical output of this system is used to operate the heat pump or an air-conditioning unit, while the thermal output of the collectors is used to maintain the source-side temperature of the heat pump at approximately 15 °C all year round, thus maximising the heat-pump or air-conditioning COPs, and therefore enabling a reduced electricity consumption. It is found that the temporal resolution (e.g. hourly, daily, yearly) of the simulations strongly affects their predicted system performance. Detailed hourly calculations of these systems using TRNSYS have proven that such PV-T systems are actually capable of covering 60% of the combined heating demands and almost 100% of the cooling demands of the examined households in middle and low European-latitude regions.

Moreover, the costs of solar thermal, PV and PV-T modules and systems have been estimated and the overall/total levelised cost of energy generated (LCOE) over 20 years of operation has been calculated. It has been found that, for PV-T systems, the LCOE is mainly influenced by the system size, which will be larger at higher latitudes (lower irradiance). Nevertheless, the calculated LCOE for the proposed solution under the assumptions listed in Section 3 varies between 0.06 and 0.12 €/kW h, which is lower than the LCOE of small-scale PV-only installations in Europe. It should be noted that for PV only, the LCOE is estimated on the basis of the electricity generated, whereas for the PV-T systems it has been defined so as to account for all energy outputs of the system.

Finally, important barriers for the market adoption of PV-T technology have been identified, which act to limit the PV-T market size. These include: high initial costs, and uncertainties caused by poor knowledge of the technology due to its limited



penetration. National and international policies can assist in overcoming the barriers, especially those associated with the upfront costs. Incentives for early deployment should be considered as learning investments, which will be recovered, so these must be wisely spent in ambitious projects, and the results should be monitored and widely shared. Demonstration projects exploring the potential of PV-T co-generation or tri-generation systems should be encouraged, supported and advertised to the public, to increase the awareness of this technology and accelerate the adoption rates of these systems.

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